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Structures of Three Inclusion Compounds of Cholanamide with Either (*S*)-Enantiomer, (*R*)-Enantiomer or an Optically Resolved Mixture of Butan-2-ol

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Abstract

The three types of inclusion compounds of cholanamide (CAM, 3α,7α,12α-trihydroxy-5β-cholan-24-amide) have been crystallized from the solutions of (*S*)-butan-2-ol (CAMSB), (*R*)-butan-2-ol (CAMRB) and racemic butan-2-ol (CAMSRB), respectively. The crystal structures have been determined. The three crystal structures are isomorphous to each other and revealed that the host CAM molecules form the same layered arrangements, providing channel spaces for the guest butan-2-ol molecules. As expected, the CAMSB and CAMRB crystals include the pure (*S*)- and (*R*)-enantiomers of butan-2-ol, whereas the (*S*)-enriched mixture of enantiomers is accommodated in CAMSRB with a molar ratio between the host CAM and guest butan-2-ol molecules of 1:1. The hydrogen-bond network is rigidly formed between the CAM molecules and also between CAM and butan-2-ol molecules. CAMSB and CAMRB have slightly different unit-cell dimensions: the channels in CAMRB have a larger section, resulting in a larger unit-cell volume. In CAMSRB, although both enantiomers of the guest alcohol are included, the (*S*)-enantiomer is more abundant, indicating that the optical resolution occurs during the crystallization step.

1. Introduction

Cholic acid (CA, 3α,7α,12α-trihydroxy-5β-cholan-24-oic acid), a typical steroidal bile acid, is known to be able to accommodate a variety of organic guest molecules in tunnel-like spaces in its crystals, usually termed channels, which was first confirmed by the crystal structure analysis of the inclusion compound of cholic acid with acetophenone (Miki *et al.*, 1988). It was also found that the CA inclusion compounds have an ability of optical resolution for the guest chiral molecules, when CA crystallized from a solution of racemic lactones (Miki, Kasai, Shibakami, Takemoto & Miyata, 1991). On the other hand, CA also crystallized without inclusion of any guest molecule (Miki *et al.*, 1990) and the obtained no-guest crystals indicated the guest-responsive structural change with intercalation phenomena (Miyata *et al.*, 1990).

Cholanamide (CAM, 3α,7α,12α-trihydroxy-5β-cholan-24-amide), another steroidal bile acid in which the carboxylic OH group of CA is replaced by NH_2, as shown in Fig. 1, can also accommodate the guest molecules in similar channels (Sada, Kondo, Miyata, Tamada & Miki, 1993; Sada, Kondo, Miyata & Miki, 1994). In CAM inclusion compounds, however, hydrogen bonds between the host and guest molecules are formed, which were not observed in the case of CA (Sada, Kondo, Miyata, Tamada & Miki, 1993). By host–guest hydrogen bonding, the CAM molecules can accommodate the guest molecules more tightly than CA. When the guest molecule has a donor for hydrogen bonding such as the OH group of alcohols, an additional hydrogen bond is formed between the host and guest molecules, and the guest molecules are fixed in the channels by two hydrogen bonds (Sada, Kondo, Miyata & Miki, 1994). More recently, it was shown that the optical resolution of a wide range of aliphatic alcohols can be performed by the inclusion method using CAM as a host molecule (Sada, Kondo & Miyata, 1995).

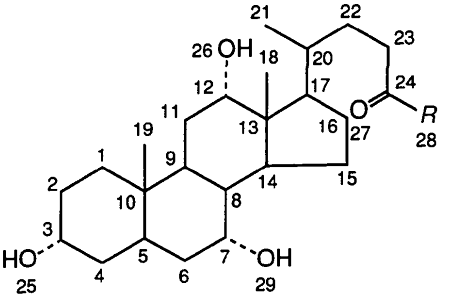

Fig. 1. Schematic structure and the atomic numbering system of cholic acid (CA, R = OH) and cholanamide (CAM, R = NH_2).

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Table 1. *Experimental details*

	CAMSB	CAMRB	CAMSRB
Crystal data			
Chemical formula	$C_{28}H_{51}NO_5$	$C_{28}H_{51}NO_5$	$C_{28}H_{51}NO_5$
Chemical formula weight	481.71	481.71	481.71
Cell setting	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1$	$P2_1$	$P2_1$
a (Å)	13.226 (1)	13.286 (1)	13.251 (1)
b (Å)	7.871 (2)	7.853 (1)	7.869 (1)
c (Å)	14.028 (1)	14.075 (1)	14.045 (1)
β (°)	104.71 (1)	105.12 (1)	104.82 (1)
V (Å^3)	1412.5 (4)	1417.6 (3)	1415.9 (3)
Z	2	2	2
D_x (Mg m^{-3})	1.133	1.128	1.130
Radiation type	Mo $K\alpha$	Mo $K\alpha$	Mo $K\alpha$
Wavelength (Å)	0.71073	0.71073	0.71073
No. of reflections for cell parameters	25	25	25
θ range (°)	28.3–29.8	23.5–29.4	22.5–29.3
μ (mm^{-1})	0.0710	0.0707	0.0708
Temperature (K)	298	298	298
Crystal form	Prism	Prism	Prism
Crystal size (mm)	0.50 × 0.30 × 0.20	0.50 × 0.25 × 0.15	0.60 × 0.20 × 0.10
Crystal color	Colorless	Colorless	Colorless
Data collection			
Diffractometer	Rigaku AFC-5*R*	Rigaku AFC-5*R*	Rigaku AFC-5*R*
Data collection method	$\theta/2\theta$	$\theta/2\theta$	$\theta/2\theta$
Absorption correction	Azimuthal scan	Azimuthal scan	Azimuthal scan
T_{min}	0.98	0.97	0.98
T_{max}	1.00	1.00	1.00
No. of measured reflections	2882	2896	2888
No. of independent reflections	2760	2774	2766
No. of observed reflections	2133	1895	1473
Criterion for observed reflections	$I > 3\sigma(I)$	$I > 3\sigma(I)$	$I > 3\sigma(I)$
R_{int}	0.010	0.012	0.018
θ_{max} (°)	25.25	25.25	25.25
Range of h, k, l	$0 \rightarrow h \rightarrow 16$ $0 \rightarrow k \rightarrow 9$ $-17 \rightarrow l \rightarrow 17$	$0 \rightarrow h \rightarrow 16$ $0 \rightarrow k \rightarrow 9$ $-17 \rightarrow l \rightarrow 17$	$0 \rightarrow h \rightarrow 16$ $0 \rightarrow k \rightarrow 9$ $-17 \rightarrow l \rightarrow 17$
No. of standard reflections	3	3	3
Frequency of standard reflections	Every 150 reflections	Every 150 reflections	Every 150 reflections
Intensity decay (%)	0.4	3.0	0.1
Refinement			
Refinement on	F	F	F
R	0.050	0.068	0.051
wR	0.060	0.082	0.058
S	2.30	2.63	2.06
No. of reflections used in refinement	2133	1895	1473
No. of parameters used	429	429	438
H-atom treatment	H atoms of butan-2-ol were not refined; positions of other H atoms were refined	H atoms of butan-2-ol were not refined; positions of other H atoms were refined	H atoms of butan-2-ol were not refined; positions of other H atoms were refined
Weighting scheme	$w = 4\vert F\vert^2/\sigma^2(F)$	$w = 4\vert F\vert^2/\sigma^2(F)$	$w = 4\vert F\vert^2/\sigma^2(F)$
$(\Delta/\sigma)_{max}$	0.05 for host, 0.25 for guest	0.10 for host, 2.79 for guest	0.07 for host, 1.03 for guest
$\Delta\rho_{max}$ (e Å^{-3})	0.34	0.23	0.16
$\Delta\rho_{min}$ (e Å^{-3})	−0.24	−0.31	−0.22
Extinction method	None	None	None
Source of atomic scattering factors	*International Tables for X-ray Crystallography* (1974, Vol. IV)	*International Tables for X-ray Crystallography* (1974, Vol. IV)	*International Tables for X-ray Crystallography* (1974, Vol. IV)

We obtained three types of inclusion crystals when CAM was recrystallized from (*S*)-, (*R*)- and racemic butan-2-ol solutions, respectively. It was found by thermal analyses and solution ^{1}H NMR studies that all the crystals have 1:1 host:guest stoichiometry (Sada, Kondo, Miyata & Miki, 1994). We report here the crystal structures of the CAM inclusion compounds which accommodate pure (*S*)-butan-2-ol (CAMSB), pure (*R*)-butan-2-ol (CAMRB) and both (*S*)- and (*R*)-butan-2-ols (CAMSRB). In the case of CAMSRB both chemical and crystallographic analyses indicated that the (*S*)-enantiomer is preferentially included in the crystals. As butan-2-ol is the smallest aliphatic secondary alcohol which can allow enantiomeric configurations, the comparison of the three crystal structures provides a simple model to study optical resolution during the crystallization process. As far as we know, this is the first example of the preparation and structure determination by means of crystallography of different host–guest crystals in which the same chiral host molecules include either only the (*S*)-enantiomer, only the (*R*)-enantiomer or a mixture of both enantiomers as guest molecules.

2. Experimental

CAM and butan-2-ols were commercially available. Colorless crystals of CAMSB, CAMRB and CAMSRB were grown from (*S*)-, (*R*)- and racemic butan-2-ol solutions of CAM, respectively. Well shaped crystals were mounted on a Rigaku AFC-5*R* diffractometer with graphite-monochromated Mo $K\alpha$ radiation. Crystal data and the experimental conditions are presented in Table 1. Unit-cell parameters were determined by least-squares fit of 2θ values of 25 centered reflections. Intensities were collected using the θ–2θ scan technique to a maximum 2θ value of 50.5° ($\sin\theta/\lambda = 0.600$ Å^{-1}). The scan width of $(1.0 + 0.14\tan\theta)^\circ$ was employed with a scan speed of 8° min^{-1} in 2θ. Stationary background counts were recorded on each side of each reflection. The ratio of peak counting time to background counting time was 2:1. Reflections collected with index ranges $h = 0$–16, $k = 0$–9 and $l = -17$–17 were corrected for the intensity decay evaluated by three standard reflections remeasured every 150 reflections. The usual Lorentz and polarization corrections were made. The data were also corrected for absorption based on the azimuthal scan method, but not for extinction.

The structure of CAMRB was initially solved by direct methods using *MITHRIL* (Gilmore, 1984) and *DIRDIF* (Beurskens, 1984), which easily determined the positions of all non-H atoms of the CAM molecule. Subsequently, these atomic coordinates of the CAM molecule in CAMRB were used for the initial models of CAMSB and CAMSRB, because of the isomorphism between the three crystals. The positions of the non-H atoms of butan-2-ol were located from the subsequent Fourier synthesis in each compound. The H atoms were also found on the difference-Fourier maps at the corresponding calculated positions, although those of the guest molecules showed a very low peak in the map. The refinement was performed by the full matrix least-squares method. Non-H atoms were refined anisotropically, whereas only the positional parameters were refined for the H atoms of the CAM molecules with the equivalent isotropic thermal parameters of the connecting non-H atoms. Reflections with $I > 3\sigma(I)$ were included in the refinement, where the function minimized was $\sum w(|F_o| - |F_c|)^2$. The weighting scheme used was $w = 4|F_o|^2/\sigma^2(|F_o|)$. The large maximum shift/error values for the guest molecules may be due to their large thermal motions. The atomic scattering factors were taken from *International Tables for X-ray Crystallography* (1974, Vol. IV). The final atomic parameters for CAMSB, CAMRB and CAMSRB are listed in

Table 2. *Fractional atomic coordinates and equivalent isotropic displacement parameters (Å^2) for CAM and butan-2-ol**

$$U_{\rm eq} = (1/3)\Sigma_i\Sigma_j U_{ij}a_i^* a_j^* \mathbf{a}_i.\mathbf{a}_j.$$

	x	y	z	$B_{\rm eq}$
CAMSB				
C1	1.1651 (4)	0.857 (1)	0.8934 (3)	4.3
C2	1.1185 (4)	0.828 (1)	0.9812 (3)	4.4
C3	1.1489 (4)	0.655 (1)	1.0263 (3)	4.3
C4	1.1135 (4)	0.522 (1)	0.9482 (3)	4.0
C5	1.1553 (3)	0.546 (1)	0.8568 (3)	4.0
C6	1.1178 (4)	0.403 (1)	0.7819 (3)	4.1
C7	1.0039 (3)	0.418 (1)	0.7249 (3)	3.5
C8	0.9807 (3)	0.596 (1)	0.6783 (3)	3.2
C9	1.0146 (3)	0.739 (1)	0.7545 (3)	3.2
C10	1.1330 (3)	0.725 (1)	0.8095 (3)	3.7
C11	0.9842 (3)	0.912 (1)	0.7045 (3)	3.8
C12	0.8689 (3)	0.929 (1)	0.6491 (3)	3.5
C13	0.8357 (3)	0.784 (1)	0.5723 (3)	3.2
C14	0.8659 (3)	0.615 (1)	0.6272 (3)	3.2
C15	0.8139 (4)	0.481 (1)	0.5532 (3)	4.1
C16	0.7116 (4)	0.563 (1)	0.4973 (4)	4.6
C17	0.7176 (3)	0.755 (1)	0.5263 (3)	3.5
C18	0.8931 (4)	0.809 (1)	0.4904 (3)	4.0
C19	1.2029 (4)	0.757 (1)	0.7382 (4)	5.5
C20	0.6582 (3)	0.867 (1)	0.4404 (3)	3.9
C21	0.6671 (5)	1.056 (1)	0.4617 (5)	5.1
C22	0.5425 (4)	0.814 (1)	0.4107 (4)	4.8
C23	0.4825 (4)	0.865 (1)	0.3102 (5)	7.6
C24	0.3724 (4)	0.799 (1)	0.2820 (4)	6.7
O25	1.1001 (3)	0.630	1.1051 (2)	5.4
O26	0.8076 (3)	0.929 (1)	0.7203 (2)	4.3
O27	0.3545 (4)	0.651 (1)	0.3011 (4)	10.7
N28	0.3003 (4)	0.905 (1)	0.2368 (3)	8.0
O29	0.9327 (2)	0.393 (1)	0.7844 (2)	4.1
C1G	0.496 (1)	1.355 (3)	0.196 (2)	32.8
C2G	0.396 (1)	1.325 (2)	0.136 (2)	15.4
C3G	0.388 (2)	1.206 (2)	0.043 (2)	21.2
C4GS	0.422 (2)	1.255 (3)	−0.033 (2)	28.1
O5G	0.3304 (7)	1.249 (2)	0.1816 (6)	14.9
CAMRB				
C1	1.1645 (7)	0.855 (2)	0.8953 (6)	4.7
C2	1.1184 (6)	0.833 (1)	0.9809 (5)	4.7
C3	1.1477 (7)	0.656 (1)	1.0265 (6)	4.6
C4	1.1104 (7)	0.523 (1)	0.9471 (5)	4.1
C5	1.1546 (6)	0.546 (1)	0.8591 (5)	4.2
C6	1.1162 (6)	0.405 (1)	0.7820 (6)	4.2
C7	1.0024 (6)	0.422 (1)	0.7256 (5)	3.6
C8	0.9815 (6)	0.598 (1)	0.6802 (6)	3.6
C9	1.0161 (5)	0.742 (1)	0.7545 (5)	3.1
C10	1.1333 (5)	0.726 (1)	0.8114 (5)	3.9
C11	0.9858 (6)	0.917 (1)	0.7076 (6)	3.9
C12	0.8708 (5)	0.935 (1)	0.6499 (5)	3.6
C13	0.8373 (5)	0.790 (1)	0.5732 (4)	3.1
C14	0.8670 (6)	0.621 (1)	0.6280 (5)	3.2
C15	0.8147 (6)	0.486 (1)	0.5506 (6)	4.5
C16	0.7141 (7)	0.570 (1)	0.4958 (6)	4.8
C17	0.7189 (5)	0.762 (1)	0.5270 (5)	3.7
C18	0.8922 (7)	0.816 (2)	0.4907 (6)	4.1
C19	1.2028 (7)	0.756 (2)	0.7409 (7)	5.5
C20	0.6594 (5)	0.875 (1)	0.4416 (6)	4.3
C21	0.6697 (9)	1.064 (2)	0.4626 (8)	5.6
C22	0.5431 (8)	0.822 (2)	0.4124 (9)	5.2
C23	0.4819 (6)	0.879 (2)	0.3155 (6)	7.6
C24	0.3704 (7)	0.808 (2)	0.2848 (7)	7.3
O25	1.0976 (4)	0.630	1.1054 (3)	5.6
O26	0.8096 (5)	0.933 (1)	0.7209 (4)	4.5
O27	0.3556 (6)	0.654 (2)	0.3001 (6)	10.8
N28	0.2987 (5)	0.915 (2)	0.2420 (6)	8.6
O29	0.9312 (3)	0.395 (1)	0.7827 (3)	4.2
C1G	0.484 (3)	1.369 (6)	0.179 (4)	30.8
C2G	0.383 (2)	1.335 (4)	0.145 (3)	21.8
C3G	0.366 (3)	1.220 (6)	0.043 (2)	33.6
C4GR	0.525 (1)	1.505 (3)	0.145 (1)	16.2
O5G	0.345 (2)	1.243 (3)	0.203 (1)	26.7

Table 2 (*cont.*)

	x	*y*	*z*	B_{eq}
CAMSRB				
C1	1.1637 (7)	0.860 (2)	0.8944 (6)	4.7
C2	1.1186 (7)	0.829 (2)	0.9815 (6)	4.5
C3	1.1482 (8)	0.655 (2)	1.0257 (6)	4.5
C4	1.1116 (8)	0.522 (2)	0.9484 (5)	4.3
C5	1.1541 (6)	0.545 (2)	0.8572 (6)	4.0
C6	1.1162 (6)	0.401 (2)	0.7831 (6)	4.3
C7	1.0034 (6)	0.418 (2)	0.7247 (6)	3.8
C8	0.9812 (6)	0.595 (1)	0.6781 (5)	3.1
C9	1.0148 (6)	0.740 (2)	0.7540 (6)	3.3
C10	1.1328 (6)	0.726 (1)	0.8105 (5)	3.6
C11	0.9845 (6)	0.912 (1)	0.7042 (6)	3.7
C12	0.8691 (6)	0.930 (2)	0.6496 (5)	3.5
C13	0.8366 (5)	0.787 (1)	0.5724 (5)	3.1
C14	0.8658 (6)	0.617 (2)	0.6267 (6)	3.1
C15	0.8145 (7)	0.483 (2)	0.5520 (6)	4.1
C16	0.7124 (7)	0.565 (2)	0.4963 (7)	4.4
C17	0.7181 (6)	0.757 (2)	0.5264 (6)	3.6
C18	0.8926 (7)	0.811 (2)	0.4916 (6)	4.0
C19	1.2029 (6)	0.753 (2)	0.7389 (6)	5.3
C20	0.6582 (6)	0.871 (2)	0.4407 (6)	4.1
C21	0.669 (1)	1.062 (2)	0.4621 (8)	5.4
C22	0.5424 (7)	0.815 (2)	0.4117 (7)	5.1
C23	0.4832 (7)	0.867 (2)	0.3098 (7)	7.6
C24	0.3719 (8)	0.798 (2)	0.2834 (7)	7.2
O25	1.0990 (7)	0.630	1.1052 (5)	5.7
O26	0.8087 (6)	0.929 (1)	0.7205 (5)	4.5
O27	0.3544 (6)	0.651 (2)	0.3009 (6)	10.5
N28	0.2995 (6)	0.900 (2)	0.2411 (6)	8.0
O29	0.9312 (5)	0.395 (1)	0.7832 (4)	4.3
C1G	0.494 (3)	1.350 (3)	0.193 (3)	39.4
C2G	0.393 (2)	1.322 (2)	0.128 (3)	20.4
C3G	0.379 (3)	1.200 (3)	0.043 (2)	21.5
C4GS†	0.422 (4)	1.262 (4)	−0.037 (3)	22.4
C4GR†	0.517 (5)	1.500 (5)	0.153 (7)	32.8
O5G	0.339 (2)	1.247 (2)	0.190 (1)	19.0

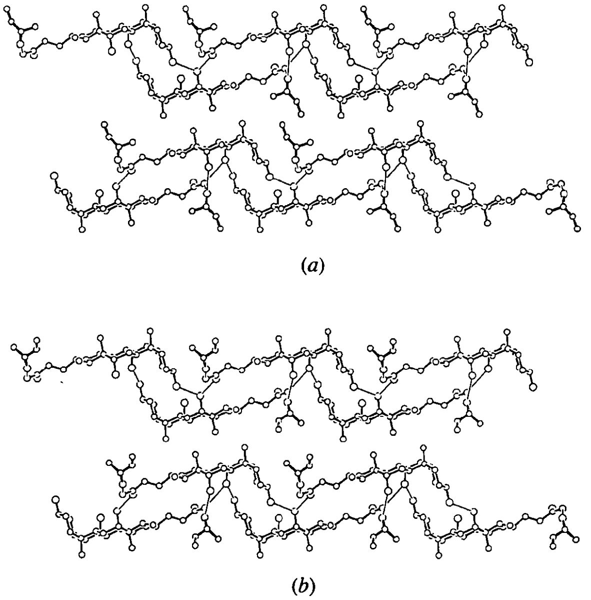
* The atomic numbering systems for the guest butan-2-ol molecule are: C1G–C2G(OH)–C3G–C4GS for CAMSB, C4GR–C1G–C2G(OH)–C3G for CAMRB and C4GR–C1G–C2G(OH)–C3G–C4GS for CAMSRB. † Occupancy factors in CAMSRB are: C4GS 0.61 and C4GR 0.39.

Table 2.* All computations were performed on a MicroVAXII computer using the *TEXSAN* crystallographic software packing (Molecular Structure Corporation, 1989).

3. Results and discussion

The crystal structures of CAMSB and CAMRB are shown in Fig. 2. The bond distances and angles for the CAM molecule (Table 3 for CAMSB) in the three crystals are as expected for steroidal compounds, within experimental error, whereas some less accurate values for guest atoms are due to their large thermal motions. The arrangement of CAM molecules is essentially the same in both CAMSB and CAMRB (Fig. 2). The CAM molecules are arranged so that the OH and NH_2 groups are associated to form hydrophilic layers, whereas the CH_3 groups are located at the side of the hydrophobic layers, as found in the CAM inclusion compounds with 1,4-dioxane and propan-2-ol (Sada, Kondo, Miyata, Tamada & Miki, 1993; Sada, Kondo, Miyata & Miki, 1994). Such amphiphilic antiparallel layered structures are also observed in the CA inclusion crystal structures, although the arrangements between hydrophobic layers are slightly different (Miki *et al.*, 1988). There are four types of hydrogen bonds between the CAM molecules within the hydrophilic layers, forming a three-dimensional rigid network (Table 4). The layered structures of CAM molecules provide channels parallel to the *b* axis in which butan-2-ol molecules are accommodated (Fig. 2). In addition to the hydrogen bonds between the host molecules, both CAMSB and CAMRB crystals have two hydrogen bonds between host and guest molecules (Table 4), as found in the CAM inclusion compound with propan-2-ol (Sada, Kondo, Miyata & Miki, 1994).

As shown in Fig. 3, the inclusion mode of the guest molecules is different in CAMSB and CAMRB. Due to the different positions of the terminal C atom C4G of the ethyl group, the C3G—C4GS bond in CAMSB is almost perpendicular to the channel direction, whereas the corresponding C1G—C4GR bond in CAMRB is almost parallel to it. Fig. 4 shows the structures of the guest butan-2-ol molecules accommodated in the channels of CAM. Atoms O5G, C1G, C2G and C3G occupy essentially similar positions in both CAMSB and CAMRB, although they are slightly shifted (see the orientations of the O5G—C2G bond in Fig. 4). These



(*a*)

(*b*)

Fig. 2. The crystal structure of (*a*) CAMSB and (*b*) CAMRB as viewed down the crystallographic *b* axis drawn by *ORTEPII* (Johnson, 1976). H atoms are omitted for clarity and the hydrogen bonds are shown by thin lines.

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*Lists of structure factors, anisotropic temperature factors, H-atom coordinates and bond distances and angles for non-H atoms have been deposited with the IUCr (Reference: AS0702). Copies may be obtained through The Managing Editor, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HU, England.

Table 3. *Selected geometric parameters* (Å, °) *for CAMSB*

C1—C2	1.528 (7)	C11—C12	1.532 (6)
C1—C10	1.546 (7)	C12—C13	1.554 (6)
C2—C3	1.512 (7)	C12—O26	1.437 (5)
C3—C4	1.502 (7)	C13—C14	1.538 (6)
C3—O25	1.428 (6)	C13—C17	1.548 (6)
C4—C5	1.531 (6)	C13—C18	1.542 (6)
C5—C6	1.534 (7)	C14—C15	1.517 (7)
C5—C10	1.553 (7)	C15—C16	1.524 (7)
C6—C7	1.520 (6)	C16—C17	1.562 (8)
C7—C8	1.544 (6)	C17—C20	1.538 (6)
C7—O29	1.422 (5)	C20—C21	1.516 (8)
C8—C9	1.539 (6)	C20—C22	1.538 (6)
C8—C14	1.513 (6)	C22—C23	1.487 (7)
C9—C10	1.564 (6)	C23—C24	1.501 (8)
C9—C11	1.538 (6)	C24—O27	1.232 (9)
C10—C19	1.545 (7)	C24—N28	1.304 (10)
C2—C1—C10	115.1 (4)	C11—C12—C13	110.9 (4)
C1—C2—C3	110.7 (4)	C11—C12—O26	108.2 (3)
C2—C3—C4	108.8 (4)	C13—C12—O26	111.8 (3)
C2—C3—O25	108.9 (4)	C12—C13—C14	107.2 (3)
C4—C3—O25	110.5 (4)	C12—C13—C17	118.3 (4)
C3—C4—C5	114.4 (4)	C12—C13—C18	108.5 (4)
C4—C5—C6	111.1 (4)	C14—C13—C17	100.8 (3)
C4—C5—C10	113.6 (4)	C14—C13—C18	111.7 (4)
C6—C5—C10	112.3 (4)	C17—C13—C18	110.1 (3)
C5—C6—C7	114.1 (4)	C8—C14—C13	115.1 (4)
C6—C7—C8	110.9 (4)	C8—C14—C15	118.8 (4)
C6—C7—O29	113.3 (3)	C13—C14—C15	104.1 (3)
C8—C7—O29	106.5 (3)	C14—C15—C16	104.3 (4)
C7—C8—C9	112.2 (3)	C15—C16—C17	107.2 (4)
C7—C8—C14	111.0 (4)	C13—C17—C16	103.3 (4)
C9—C8—C14	109.7 (4)	C13—C17—C20	120.2 (4)
C8—C9—C10	111.7 (4)	C16—C17—C20	111.6 (4)
C8—C9—C11	109.5 (3)	C17—C20—C21	114.2 (4)
C10—C9—C11	113.6 (4)	C17—C20—C22	109.4 (4)
C1—C10—C5	107.4 (4)	C21—C20—C22	110.0 (5)
C1—C10—C9	112.0 (4)	C20—C22—C23	116.0 (5)
C1—C10—C19	106.8 (4)	C22—C23—C24	113.9 (6)
C5—C10—C9	109.4 (3)	C23—C24—O27	119.8 (7)
C5—C10—C19	110.1 (4)	C23—C24—N28	116.6 (8)
C9—C10—C19	111.0 (4)	O27—C24—N28	123.6 (6)
C9—C11—C12	114.8 (4)		

Table 4. *Hydrogen-bonding distances (Å) for O—O and N—O*

	CAMSB	CAMRB	CAMSRB
$O25^{(i)}—H\cdots O26^{(ii)}$	2.911 (5)	2.884 (7)	2.908 (10)
$O26^{(ii)}—H\cdots O27^{(iii)}$	2.723 (6)	2.752 (13)	2.735 (12)
$N28^{(iii)}—H\cdots O29^{(iv)}$	3.021 (6)	2.987 (9)	2.988 (9)
$O29^{(iv)}—H\cdots O25^{(i)}$	2.687 (5)	2.697 (7)	2.699 (10)
$N28^{(iii)}—H\cdots O5G^{(iii)}$	2.872 (15)	2.737 (29)	2.905 (25)
$O5G^{(iii)}—H\cdots O26^{(iv)}$	2.917 (8)	2.956 (30)	2.953 (25)

Symmetry codes: (i) x, y, z; (ii) $2 - x, y - \frac{1}{2}, 2 - z$; (iii) $1 + x, y, 1 + z$; (iv) $2 - x, \frac{1}{2} + y, 2 - z$.

differences in the inclusion mode of the guest molecules result in a unit-cell volume of CAMRB slightly larger than that of CAMSB. The (*R*)-butan-2-ol molecules in CAMRB are accommodated in channels having a larger section (the *a* and *c* axes are longer) than those for CAMSB, which probably allows higher mobility of the guest molecules. This is connected with the larger thermal parameters refined for the guest butan-2-ol atoms and the lower precision of refined parameters, such as the *R* value, in CAMRB than CAMSB.

The CAMSRB crystals were obtained from racemic butan-2-ol solutions. The arrangement of CAM molecules is quite similar to those found in both CAMSB and CAMRB. Bond distances and angles are also similar to those found in CAMSB and CAMRB. For this crystal, an enantiomeric excess (e.e.) of 17% of (*S*)-butan-2-ol was evaluated (Sada, Kondo & Miyata, 1995). This implied that both enantiomers of butan-2-ol are accommodated, although the (*S*)-enantiomer is preferentially included. Accordingly, the unit-cell dimensions of CAMSRB show intermediate values between those of CAMSB and CAMRB (see Table 1). The structures of butan-2-ol molecules in CAMSRB are also shown in Fig. 4. Atoms O5G, C1G, C2G and C3G are located at intermediate positions between those found in CAMSB and CAMRB. The terminal C atoms C4G of the ethyl group in both enantiomeric models take positions similar to those found in the pure enantiomers of CAMSB and CAMRB. They could be refined with partial occupancy factors, which were calculated as 0.61 (for C4GS) and 0.39 (for C4GR) for (*S*)- and (*R*)-enantiomers, respectively. These values indicate a slightly higher chiral selectivity than expected from the e.e. value. However, for the random crystals used in the assay, the e.e. value is probably underestimated due to unavoidable contamination by the mother liquor. This is not the case for the unique well shaped crystals used for X-ray diffraction study. The existence of both enantiomers in CAMSRB is also confirmed by the fact that both enantiomeric models of the guest molecules could be refined and converged to reliable positions in the channel of the host CAM molecules. This is in contrast to the case of the CA inclusion crystals with γ-valerolactone, where only the (*S*)-enantiomer of the

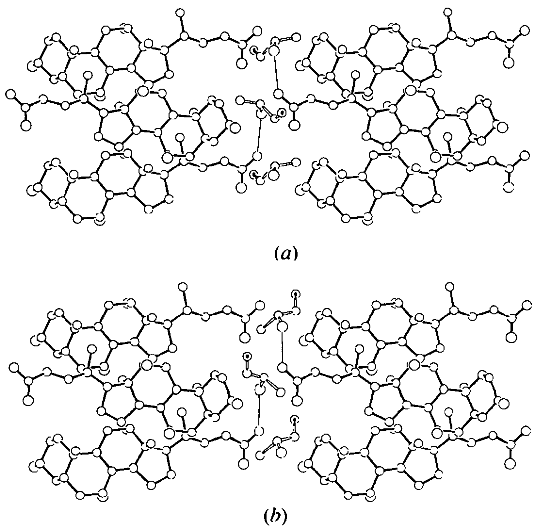

Fig. 3. The crystal structure of (*a*) CAMSB and (*b*) CAMRB as viewed down the crystallographic *a* axis, where the channels formed by the host CAM molecules are seen as a vertical groove. H atoms are omitted for clarity and the hydrogen bonds between N28 and O5G are shown by thin lines. Atoms C4GS and C4GR are indicated by asterisks for CAMSB and CAMRB.

guest molecules could be found and refined (Miki, Kasai, Shibakami, Takemoto & Miyata, 1991), even though the e.e. value was evaluated as only 28% (Miyata, Shibakami & Takemoto, 1988). This is the first case in which the host molecules can accommodate the pure (*S*)- and (*R*)-enantiomers as well as a mixture of both enantiomers in similar channels. The slight difference in interactions between the host and guest molecules induced a little volume change of the unit cell. It is a widely accepted concept that crystallization favors the production of tight crystals (Kitaigorodsky, 1973). We propose that the (*S*)-enantiomer is included in a higher content than the (*R*)-enantiomer in CAMSRB during crystallization from racemic butan-2-ol solutions, because its accommodation in the channels results in a smaller unit-cell volume which allows closer packing between host and guest molecules. This may be a plausible explanation for the observed chiral selectivity.

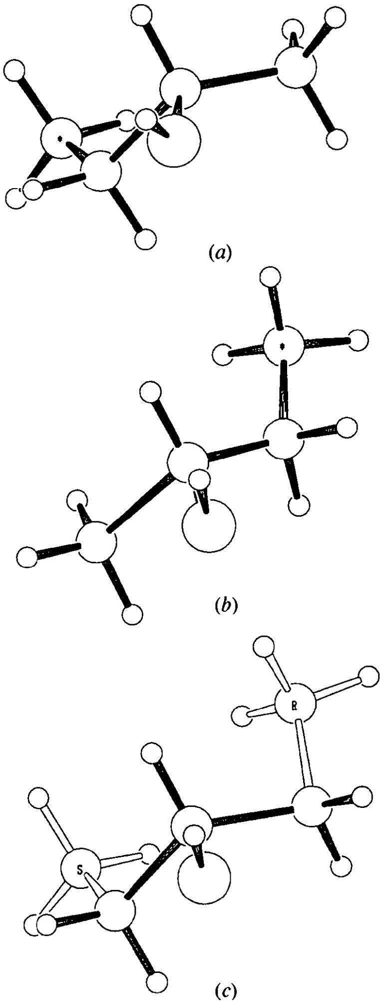

Fig. 4. The structures of the guest butan-2-ol molecules observed in (*a*) CAMSB, (*b*) CAMRB and (*c*) CAMSRB, as viewed from the same direction as Fig. 3. Atoms C4GS and C4GR are indicated by asterisks for CAMSB and CAMRB, and by S and R for CAMSRB. In CAMSRB the butan-2-ol molecules are treated as a disordered model where the terminal C atoms of the ethyl groups C4GS and C4GR are independently refined with partial occupancies and the other atoms occupy the common positions in both enantiomeric models as an averaged structure. The bonds connecting with atoms C4GS and C4GR of CAMSRB are shown as open bonds.

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References

Beurskens, P. T. (1984). *DIRDIF. Direct Methods for Difference Structures - An Automatic Procedure for Phase Extension and Refinement of Difference Structure Factors.* Technical Report 1984/1. Crystallography Laboratory, Toernooiveld, 6525 ED Nijmegen, The Netherlands.

Gilmore, G. J. (1984). *J. Appl. Cryst.* **17**, 42–46.

Johnson, C. K. (1976). *ORTEP*II. Report ORNL-5138. Oak Ridge National Laboratory, Tennessee, USA.

Kitaigorodsky, A. I. (1973). *Molecular Crystals and Molecules.* New York: Academic Press.

Miki, K., Kasai, N., Shibakami, M., Chirachanchai, S., Takemoto, K. & Miyata, M. (1990). *Acta Cryst.* C**46**, 2442–2445.

Miki, K., Kasai, N., Shibakami, M., Takemoto, K. & Miyata, M. (1991). *J. Chem. Soc. Chem. Commun.* pp. 1757–1759.

Miki, K., Masui, A., Kasai, N., Miyata, M., Shibakami, M. & Takemoto, K. (1988). *J. Am. Chem. Soc.* **110**, 6594–6596.

Miyata, M., Shibakami, M., Chirachanchai, S., Takemoto, K., Kasai, N. & Miki, K. (1990). *Nature*, **343**, 446–447.

Miyata, M., Shibakami, M. & Takemoto, K. (1988). *J. Chem. Soc. Chem. Commun.* pp. 655–656.

Molecular Structure Corporation (1989). *TEXSAN. Single Crystal Structure Analysis Software.* MSC, 3200 Research Forest Drive, The Woodlands, TX 77381, USA.

Sada, K., Kondo, T. & Miyata, M. (1995). *Tetrahedron Asym.* **6**, 2655–2656.

Sada, K., Kondo, T., Miyata, M. & Miki, K. (1994). *Chem. Mater.* **6**, 1103–1105.

Sada, K., Kondo, T., Miyata, M., Tamada, T. & Miki, K. (1993). *J. Chem. Soc. Chem. Commun.* pp. 753–755.